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A New Converter Concept Providing Improved Flow Distribution and Space Utilization

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ABSTRACT

A new converter concept is introduced, which utilizes the additional space in the inlet cone of the converter. An optimized design is obtained by the application of computational fluid dynamics (CFD) and flow distribution measurements, resulting in up to 20% improved flow distribution through the substrate. In addition, the volume of the converter can be increased by approximately 15% using the same space envelope. Durability tests of the converter system have been performed using a thermal cycling test on an engine test bench for 135 hours. No deterioration of the substrate or mounting system occurred. The emissions performance was evaluated on a stationary dynamometer. The impact of the flow distribution on the temperature field and the conversion behavior during light-off and steady state operation were investigated. Under the current testing conditions, no differences in light-off behavior were determined, despite significant differences in the temperature field. Both improved flow distribution and increased converter volume contributed to better steady-state performance.

INTRODUCTION

The ongoing efforts to reduce the emissions (Table 1) for gasoline engine powered vehicles create challenges to the vehicle design engineer.

Table 1. European [1] and US emissions regulations [2]

	NMOG	CO	NO_x
EURO III (g/km)	0.2	2.3	0.15
EURO IV (g/km)	0.1	1	0.085
LEV (g/mile)	0.075	3.4	0.2
LEV II (g/mile)	0.075	3.4	0.05
ULEV (g/mile)	0.04	1.7	0.2
ULEV II (g/mile)	0.04	1.7	0.05

To achieve these very low emissions levels, integrated actions for the optimization of vehicle, engine, fuel, and aftertreatment concepts are necessary [3]. Other important factors like fuel consumption, engine performance, durability and space limitations also need to be considered during the design of the aftertreatment system. Hence advanced engine management strategies have been introduced [4], which result in faster converter light-off and higher conversion efficiency. Improved catalyst technology achieves lower light-off temperatures, higher conversion efficiency and better aging characteristics of the catalyst. Improved thermal management is achieved with new exhaust manifold design and dual wall exhaust piping [5]. Catalyst supports have been developed to achieve lower mass and higher surface area for faster light-off, higher conversion efficiencies and better space utilization [6][7]. New robust packaging concepts for ceramic supports have been introduced which withstand harsher operating environments [8]. The system integration of the single components and their optimization will result in the technical solution to fulfill future emissions challenges.

In this context the contoured converter system (Figure 1) allows a very effective utilization of the available space with improved flow distribution.

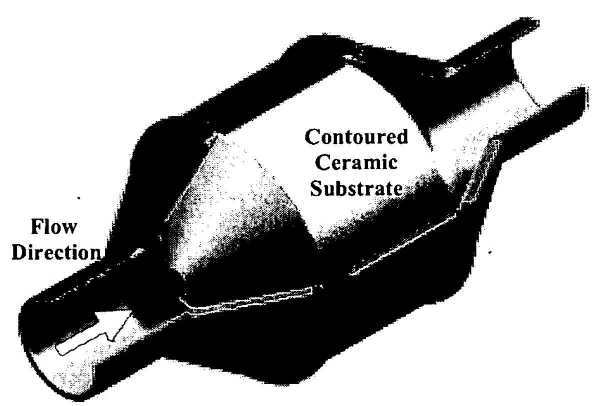

Figure 1. Converter system with contoured ceramic substrate

The advanced converter system comprises a continuous ceramic substrate with a shaped front face. Cell density and wall thickness of the substrate are not effected and can be chosen appropriately as required by the application.

FLOW DISTRIBUTION

CFD MODELING – Computational fluid dynamics (CFD) calculations were performed to evaluate the potential benefits of the contoured converter system relative to a standard converter system. CFD calculations provide a cost effective and efficient means of evaluating converter designs from the standpoint of flow uniformity and overall converter pressure drop. The CFD calculations were performed using the commercially available fluid dynamics software Fluent/UNS, a fully unstructured finite-volume method. Axisymmetric turbulent flow was simulated using Fluent/UNS's implementation of the renormalization group (RNG) k-ε turbulence model. The substrate was modeled as a laminar flow porous medium exhibiting a finite permeability in the axial direction, and zero permeability (zero flow) in the radial direction. A fully developed turbulent velocity profile was imposed as the inlet condition, while at the outlet, a constant pressure condition was imposed. The simplified CFD model was chosen to be steady, isothermal, and non-reacting.

Generic flow fields for both standard and contoured substrates are compared in Figure 2.

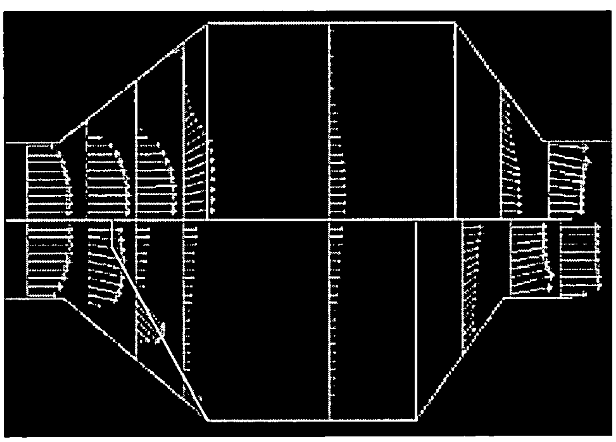

Figure 2. Flow field in the converter

The turbulent velocity profile is established in the inlet pipe. For the standard substrate, the flow through the inlet pipe can not follow the geometry of the inlet cone and starts to separate shortly after the the entrance of the diffuser. The jet through the center of the cone impinges on the substrate front face and is forced in the radial direction. The result is a very non-uniform flow distribution through the monolith. For the contoured substrate the flow is directed to the periphery of the converter. The recirculation zone is reduced to a very small area and the flow distribution throughout the substrate is more uniform.

Typical CFD results for the axisymmetric velocity profile across the monolith are shown in Figure 3 for both standard and shaped substrates at a Reynolds number of 50000.

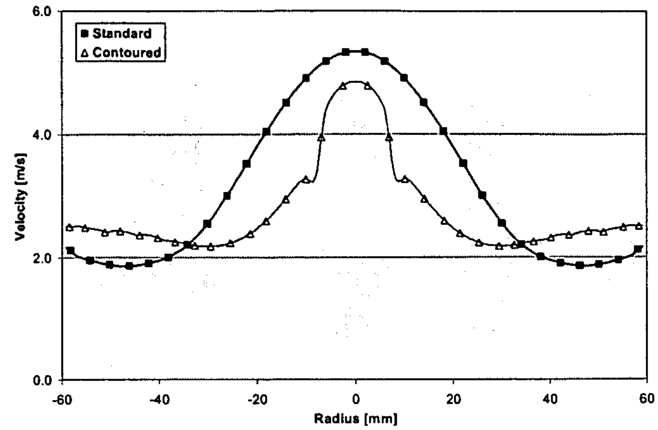

Figure 3. CFD Velocity Profile

The same outer converter dimensions were used in both cases, which resulted in a 15% overall substrate volume increase for the contoured part through the utilization of the available space in the inlet cone. Additional converter parameters are summarized in Table 2.

Table 2. Converter design parameters for emissions evaluations

	Standard	Contoured
Cell Density	62 cpcm^2	62 cpcm^2
Wall Thickness	0.165 mm	0.165 mm
Geometric Surface Area	2.74 m^2/l	2.74 m^2/l
Substrate Diameter	118.4 mm	118.4 mm
Maximum Substrate Length	101.6 mm	141.3 mm
Substrate Volume	1.12 l	1.28 l
Total Surface Area	3.07 m^2	3.51 m^2
In- & Outlet Pipe Diameter	47 mm	47 mm
In- & Outlet Cone Angle	70°	70°

The velocity profile of the shaped substrate is visibly more uniform than that of the standard substrate. The shaped design reduces the magnitude of the centerline velocity by approximately 15%, while increasing the air volumetric flow rate away from the substrate center. Since the frontal area of the substrate is proportional to the square of the radius, the flow distribution may benefit dramatically, as will be discussed.

A uniformity index was used to evaluate the flow distribution in the substrate. The calculation is based on previously published work [9], however slight modifications were necessary to account for the variation in channel

length as a result of the contoured front face. The local non-uniformity is defined as:

$$\omega_i = \frac{\sqrt{\left(v_{space,i} - \bar{v}_{space,sub}\right)^2}}{\bar{v}_{space,sub}} \quad \text{with } v_{space,i} = \frac{v_i}{L_i} \qquad (1)$$

Accumulating all the local non-uniformities and weighting them by their local area contribution results in the overall uniformity index over the cross section of the monolith structure.

$$\gamma = 1 - \frac{\omega}{2} \qquad \text{with } \omega = \frac{\iint_{A_{sub.}} \omega_i \cdot dA}{A_{sub.}} \qquad (2)$$

A uniformity value of $\gamma = 1$ describes a perfectly distributed flow, while $\gamma = 0$ describes a fully maldistributed flow. A developed laminar flow in a tube (Poiseuille flow) produces a uniformity value $\gamma = 0.75$.

The CFD calculations may be used to optimize the design of the shaped substrate for a given converter housing. Figure 4 shows the uniformity index plotted as a function of the differential angle $\Delta\alpha$ for the converter geometry described in Table 2.

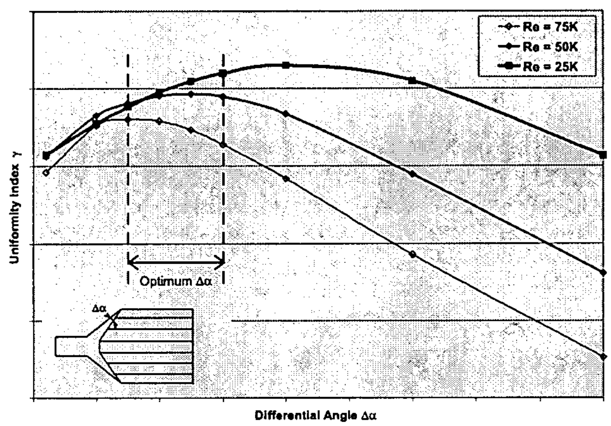

Figure 4. CFD Differential Angle Optimization

As indicated in the figure, the differential angle $\Delta\alpha$ is defined as the angle measured between the converter inlet cone and the shaped substrate. The data spans the entire range of possible differential angles from a flat-faced substrate to a shaped substrate with the tip located near the mouth of the inlet pipe. The results are presented for three different Reynolds numbers (Re=25000, 50000, 75000) based on flow condition in the inlet pipe. The calculations were performed with a fixed substrate volume of 1.12 liters, which was adjusted by varying the overall length of the contoured substrate. As expected, flow uniformity is a strong function of the Reynolds number. As the fluid inertia increases, the inlet pipe performs similar to a jet impinging at the center of the monolith, resulting in a non-uniform flow distribution.

One interesting feature of the CFD data depicted in Figure 4, is that the uniformity index passes through a maximum at a particular differential angle $\Delta\alpha$. This suggests that there is an optimum design of the shaped substrate based on the overall converter geometry. In addition, the optimal $\Delta\alpha$ is not a strong function of the Reynolds number, which allows for peak performance regardless of the upstream flow conditions. The flow uniformity benefits predicted by the CFD simulations range from 7-20% with the largest improvement occurring at Re = 75K. The shaped substrate narrows the spread of the uniformity index as a function of the Reynolds number. For Reynolds numbers in the range 25-75K, the spread in the uniformity index is nearly 20 times greater for the standard substrate as compared to the contoured substrate.

FLOW MEASUREMENTS – A cold flow bench test has been set-up to measure flow distribution and pressure drop for the converter configurations. A schematic of the experimental apparatus is depicted in Figure 5.

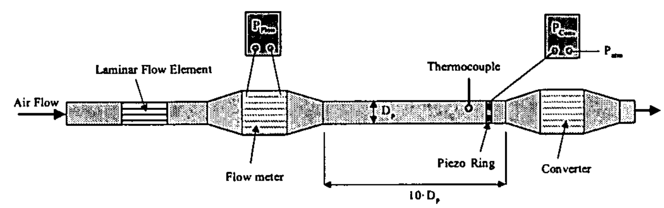

Figure 5. Set-up of the cold flow apparatus

Pressurized air first flows through a 50.8 mm diameter laminar flow element, which is placed inline with a 50.8 mm pipe to calm the flow and damp out any potential upstream fluctuations in pressure. Next, the air passes through a flow meter, which is a laminar flow element calibrated for 0-170 m^3/h corresponding to a differential pressure range of 0-2000 Pa. Thus, the experimental range of the Reynolds number, based on the inlet pipe diameter for a typical converter, is approximately 0 - 80000. The air then passes through section of pipe approximately 10 pipe diameters in length to allow the turbulent velocity profile to develop before passing through the converter. A piezo ring is located just upstream of the converter, which is connected to a differential manometer (0-2000 Pa) to measure the static pressure drop across the converter. Fluctuations in the pressure measurements at the converter were typically +/- 5 Pa. A thermocouple was inserted in the air stream just upstream of the converter to monitor the temperature. Velocity measurements were performed by removing the converter exit cones and positioning a hot wire anemometer probe 10-15 mm off the back face of the monolith. The probe was staged vertically across the symmetry plane of the substrate to obtain the radial velocity profile. Velocity and pressure measurements were performed for a standard and a shaped substrate the geometry of which is defined in Table 2.

Figure 6 shows the experimentally measured velocity profiles for the contoured and standard converter for a Reynolds number of 50000.

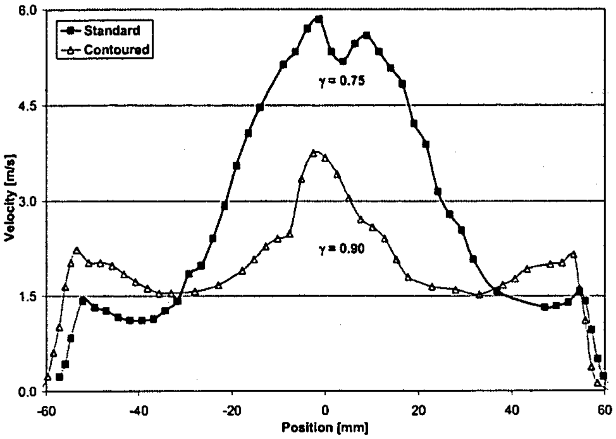

Figure 6. Measured velocity profiles

The measurements are in excellent qualitative agreement with the CFD simulation results shown in Figure 3. A quantitative comparison with the CFD results requires an accurate estimation of the upstream velocity profile, and is the subject of future investigations. As with the CFD simulations, the experimental measurements predict a reduction in the centerline velocity for the shaped substrate, with the flow distributed more evenly across the frontal area. The flow uniformity indices computed from the experimentally measured velocity profiles were $\gamma = 0.75$ and $\gamma = 0.90$ for the standard and contoured converter respectively, resulting in a 20% relative improvement in flow uniformity for the contoured design. It should be noted that the "edge effects" seen in the measured profiles are caused by the tip of the probe sampling stagnant air near the edge of the monolith.

A comparison of the static pressure drop across the converters as a function of the volumetric flow rate is shown in Figure 7.

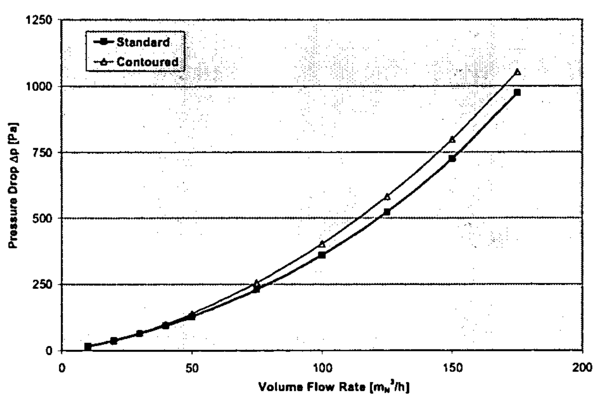

Figure 7. Pressure drop measurements

Pressure drop results for the contoured converter system are comparable to those of the standard converter system for volumetric flow rates below 50 m_N^3/h. At higher flow rates the pressure drop across the contoured converter is slightly higher than the converter with the standard substrate. At 175 m_N^3/h, or the maximum flow rate tested, the pressure drop across the contoured converter is 8% higher than the standard converter. This increase in pressure is lower than would be expected based on the 14% additional substrate volume incorporated in the contoured converter system.

FLOW VISUALIZATION – Flow visualization experiments have been performed using a liquid and injecting dye to aid in visualization. A Reynolds number of 35000 and the geometry configuration described in Table 2 have been used for these experiments. Figure 8 shows the flow field in the inlet cone of the converter with a standard substrate.

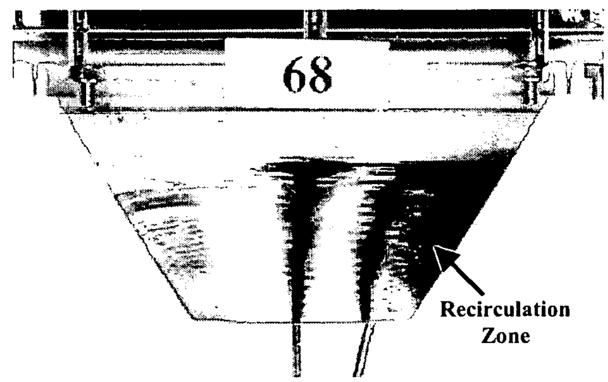

Figure 8. Inlet cone flow field for converter with standard substrate

The flow entering through the inlet pipe does not follow the cone geometry and forms a recirculation zone in the outer area of the cone. Contrasting results are obtained for the converter with the contoured substrate as shown in Figure 9.

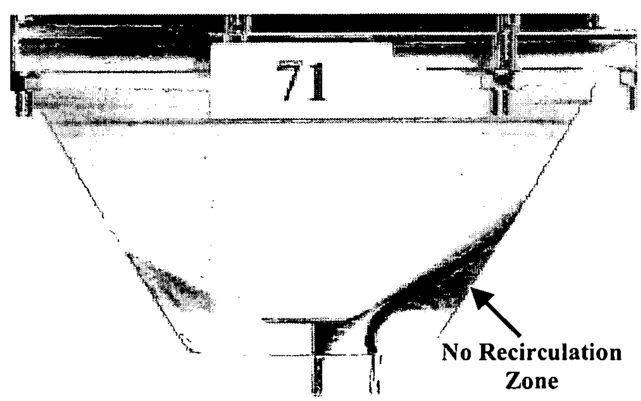

Figure 9. Inlet cone flow field for converter with contoured substrate

The narrow gap formed between the inlet cone and the substrate prevents the formation of a recirculation zone.

The effect on flow distribution through the substrate can be studied in Figure 10.

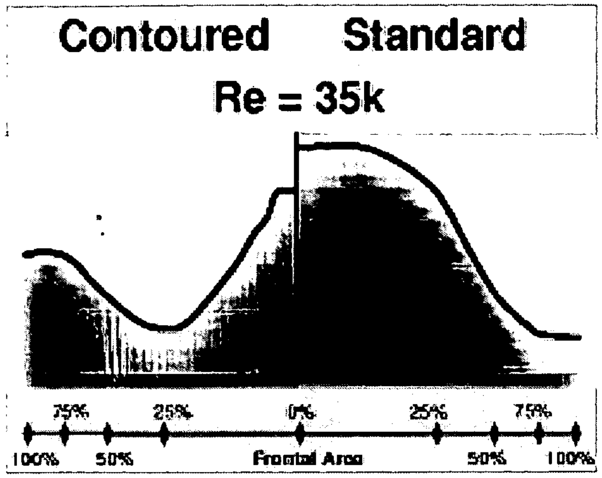

Figure 10. Flow distribution for contoured and standard substrate

The use of the contoured substrate results in an improvement of the overall flow distribution. The peak velocity is lower and the outer areas of the substrate, which contribute a significant portion of the total volume (>50%) are utilized much more efficiently. Once again good qualitative correlation to the CFD results (Figure 3) is obtained.

DURABILITY EVALUATIONS

The additional unsupported mass of the monolith and the distribution of the flow towards the exterior of the matrix raise durability concerns. Therefore it is important to evaluate the mechanical and thermal integrity of the substrate as well as the erosion resistance of the mounting system.

DESIGN – Figure 11 shows the converter design used for the durability studies.

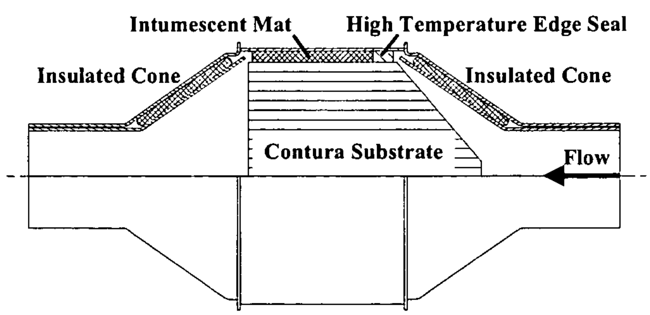

Figure 11. Converter design for durability evaluations

A converter system using a washcoated ceramic substrate with a cell density of 62 $cpcm^2$ and 0.165 mm wall thickness has been evaluated. The mounting system consists of an intumescent mat with 6200 g/m^2 basis weight and a 10 mm wide high temperature edge seal of fiber material on the inlet side. The converter was assembled using a laboratory tourniquet closure technique to a targeted nominal gap bulk density (GBD) of 1.07 g/cm^3 [10]. Double shell insulated inlet and outlet cones have been attached to the converter body. The substrate was designed to test a severe configuration, maximizing the unsupported substrate mass in the cone area and shortening the cylinder length. Hence the center of gravity of the monolith is shifted by approximately 9 mm from the middle of the cylindrical part towards the conical part of the substrate. The short length of the cylindrical part reduces the amount of holding force applied to the substrate. Table 3 summarizes the parameters of the converter used for durability testing.

Table 3. Converter design parameters for durability evaluations

Substrate Diameter	118.4 mm
Cell Density/ Wall Thickness	62cpcm^2/0.165mm
Substrate Volume	1.02 l
Substrate Mass (incl. Washcoat)	630 g
Substrate/intumescent mat Length	72 mm / 62 mm
In- & Outlet Pipe Diameter	47 mm
In- & Outlet Cone Angle	70°

TEST METHOD – An engine bench test (2.0L, 4 cylinder) was used to evaluate the durability of the converter system with the contoured substrate. The converter was mounted approximately 1 meter behind the exhaust manifold. No vibration dampers were installed between the manifold and the converter. The test consisted of 5-minute heat-up cycles followed by 5-minute cool-down cycles. During the heat-up cycle the engine was running at about 5050 rpm, which resulted in an exhaust flow of around 330 kg/h. An AC motor was coupled to the engine to run during the cool-down phase at similar revolutions. The maximum inlet temperatures achieved at the end of the heat-up cycle were around 855°C and the minimum temperatures during the end of the cool-down cycle were around 125°C. The bench test applied vibration, high temperature and thermal shock loads on the converter system. Additional erosion effects on the mounting system were also studied. The test was run for a total of 133-h resulting in a total of 800 cycles. A sample of two full subsequent cycles of the bench test is shown in Figure 12.

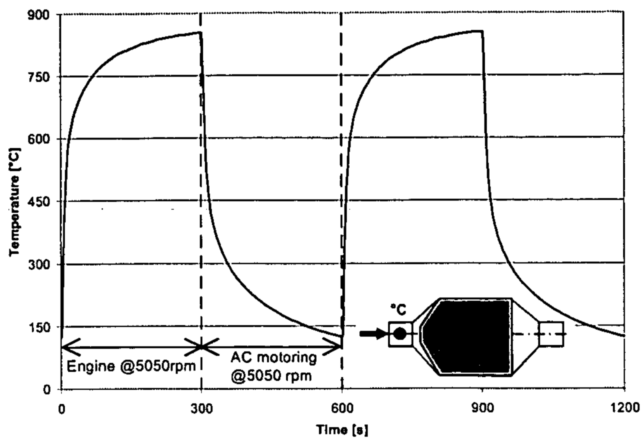

Figure 12. Inlet temperature during durability testing

RESULTS – The converter system with the contoured substrate passed the full duration of the test without failure. Visible inspection of the part did not show any erosion effects on the mounting system of the monolith or the ceramic substrate itself. Furthermore no cracks on the contoured substrate were apparent, which was also proven by using X-ray technology. A push-out force experiment [10] was performed to determine the residual holding force after the durability test (Figure 13).

The push-out results indicate the excellent condition of the mounting system. Using static calculations a value of less than 1.0 kPa can be determined to withstand the loads introduced by vibrations and pressure drop over the converter during the durability test.

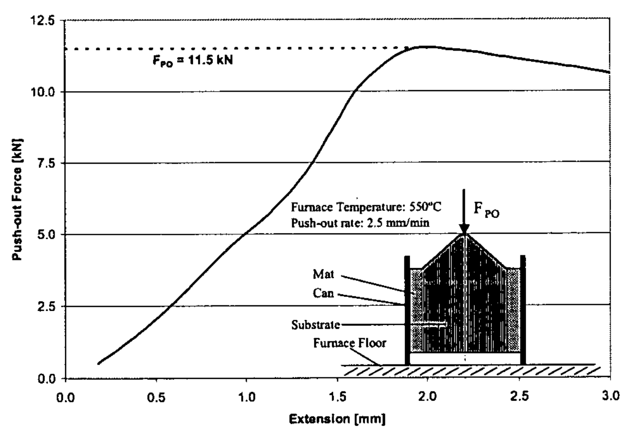

Figure 13. Residual push-out force

EMISSIONS PERFORMANCE

CONVERTER DESIGN – Two converter configurations (with standard and contoured substrate) have been evaluated and compared. Basis for the comparison was to keep the overall space envelope of the converter system constant. The results from flow distribution work were used to choose the optimum design of the converter system with the contoured substrate. The same canning design as described for the durability testing (Figure 11) and the geometry described in Table 2 was used for the emissions testing. The substrates of both converter systems were coated with the same washcoat and precious metal technology.

AGING PROCEDURE – All catalysts were subjected to 50 hours of aging on an engine dynamometer. The fuel used for aging was a commercially available premium unleaded gasoline with a sulfur concentration between 20 and 50 ppm. The aging cycle consisted of a four-step, sixty-second cycle with a total exhaust mass flow of 325 kg/h through the converter. The exhaust gas inlet temperature was set to 800 °C [3]. Maximum temperatures in the midbed position of the substrate during the oxidation phase of the aging cycle are around 940 to 950 °C.

ENGINE DYNAMOMETER EMISSIONS-TESTING – An engine dynamometer test has been developed to characterize performance differences between converter systems during the light-off phase. While the engine is running at a steady state operating point, temperature ramps are achieved by a set of heat exchangers and the flow rate can be adjusted by dynamically splitting the flow between a test and dump leg (Figure 14).

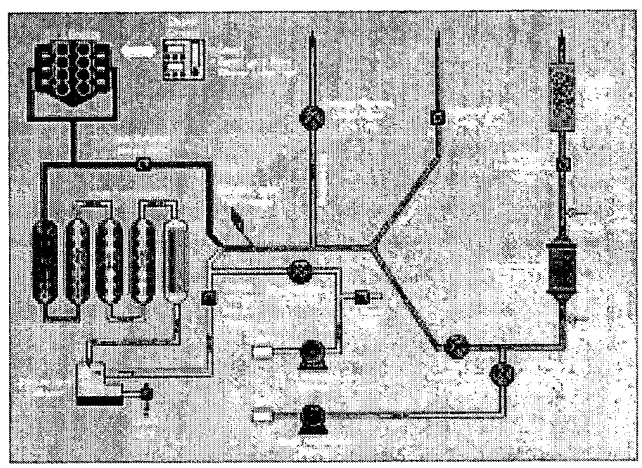

Figure 14. Set-up for engine dynamometer testing

This tool allows repetition of heat-up and light-off experiments in a timely manner and reduces variability between tests significantly [11]. Furthermore constant inlet conditions (flow rate, back pressure, heat-up rate, emissions levels, A/F ratio) can be set independently of the tested converter system, which results in an unbiased relative comparison of aftertreatment systems.

TEST PROCEDURE – Light-off tests with a lean A/F ratio (15.0) have been performed. The temperature was ramped up to a hold temperature of 400°C in about 50 seconds. The flow rate, A/F ratio and engine-out emissions were kept constant. To obtain representative results an average out of 4 tests on each system has been used for comparison. The converter systems were tested in an unaged and aged condition. To stabilize the catalyst the unaged systems have been conditioned for 4 hours at an inlet temperature of 700°C. The fuel control

was set to create ±0.5 A/F ratio swings around stoichiometry in one-minute cycles. Figure 15 summarizes the averages out of the four investigated systems (standard unaged & aged, contoured unaged & aged).

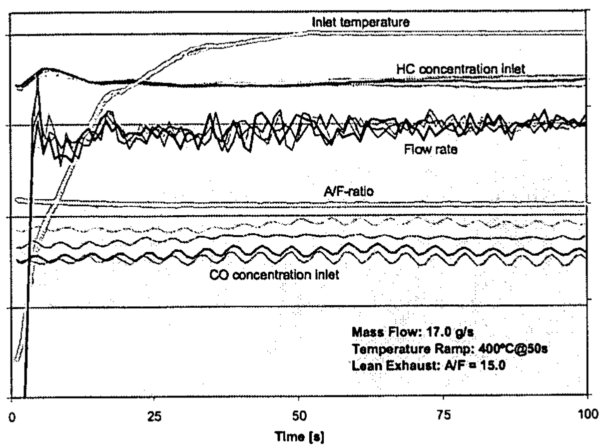

Figure 15. Repeatability of engine dynamometer testing

Good repeatability is achieved for most of the inlet parameters. Some deviations occurred for the CO-inlet concentration. However, the lower two traces are for the unaged converter tests and the upper for the aged ones, so that a comparison between the converter systems using a standard and contoured substrate is still possible.

Steady-state emissions performance was evaluated using the same set-up as for the light-off test (Figure 14). The inlet temperature was set to 400°C and three different flow rates (80, 140 & 200 kg/h) were used. The engine operated in open loop control with a 1 Hz frequency and ±0.5 A/F-ratio amplitude slightly offset from the stoichiometric point towards lean conditions. After the test converter was brought to thermal equilibrium, each test was performed for about 600 seconds. Only the aged converter sets were tested.

RESULTS – The HC conversion efficiency trace versus time (Figure 16) is a good indicator to compare the light-off performance of the different systems.

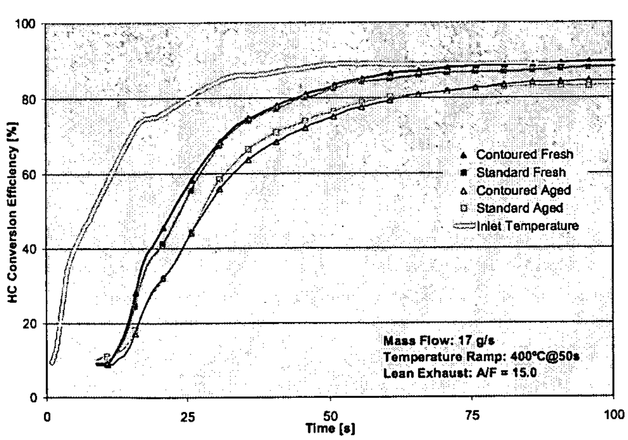

Figure 16. HC-conversion efficiency light-off testing

The performance of the two converter systems (standard & contoured) is very similar. Small differences can be determined. However, they are mostly within the error of the experiment. However, there are differences between the fresh and the aged systems. The time to reach 50% ($t_{50\%,HC}$) HC-conversion efficiency is about 5 seconds shorter for the fresh (approx. 23 s) than for the aged (approx. 28 s) converter sets. Similar results are obtained for the behavior of the CO-conversion. In general the time to reach 50% ($t_{50\%,CO}$) CO-conversion efficiency is about 10 seconds higher compared to the HC conversion. Two effects are basically determining the light-off behavior of the converter system, assuming constant exhaust conditions at the inlet:

- Light-off temperature of the catalyst

  For the fresh catalyst, there is not much difference between the two substrates expected, due to the same catalyst technology. However, for the aged catalysts, the hypothesis is that better flow distribution results in more uniform and overall less severe aging.

- The heat-up behavior of the converter

  The flow field differences for the two converter systems result in different gas velocities and therefore heat input over the cross section of the substrate.

To understand the latter effect, temperatures in different locations of the converter systems were measured (Figure 17) using very responsive thermocouples (K-type, ∅0.8 mm).

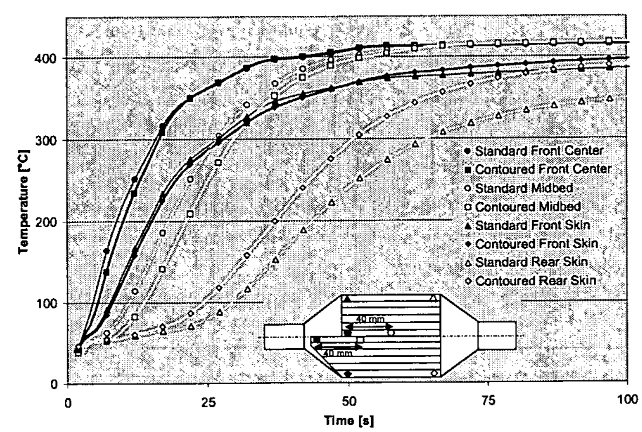

Figure 17. Temperatures light-off testing

The temperatures at the front end of the substrate near the centerline are significantly higher compared to the temperatures near the skin. The time delay in heat-up between center and skin ranges between 5 to 20 seconds. This behavior is mostly due to the heat absorption of the exhaust pipe and cones material and the resulting radial temperature profile in the gas phase over the pipe and cone cross section. At quasi steady state operation (after 90 s), a constant temperature difference between center and skin of about 30 Kelvin for the standard substrate and 20 Kelvin for the contoured substrate is achieved, due to heat losses to the environment. The

higher temperature difference for the standard substrate probably results from the lower gas velocity in the outer section of the substrate. Only minor differences in temperature between the standard and the contoured substrate are found near the front face (10 mm after the channel entry) of the converter. However, deeper in the substrate the differences become much larger. Along the centerline the standard substrate achieves higher temperatures earlier, while along the skin, the contoured substrate heats-up faster. After 100 seconds, a temperature difference of about 50 Kelvin can be measured near the back face of the converters, which is believed to be related to the lower gas velocities in the outer area of the standard substrate. The lower velocity does not overcome the heat losses to the environment and leads to a decrease in temperature over the channel length. The system using a standard substrate does not achieve thermal equilibrium even after 150 seconds as compared to the contoured system, which stabilizes approximately after 100 seconds.

To get a better understanding of the dependency between flow rate and heat-up behavior at certain substrate location, a simple one-dimensional heat-up model [11] has been applied. A heat-up rate from room temperature to 400°C of 25 seconds and a constant hold temperature of 400°C afterwards are used. Two different flow rates 17 g/s (100%) and 13.5 g/s (80%) have been evaluated. These are very similar to the values, which one would expect, from the flow distribution measurements and simulations in the outer area of the substrate for a contoured and a standard substrate.

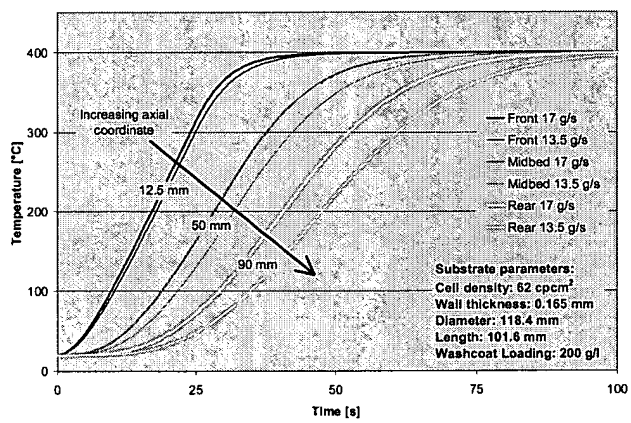

Figure 18. Temperatures heat-up simulation

The results of the model (Figure 18) show a very similar trend compared to the experimental data (Figure 17). The differences in heat-up behavior or temperature become more apparent over the length of the channel and are very small at the inlet. This allows the conclusion that the flow rate difference is the main driving force for the different heat-up behavior of standard and contoured substrate.

Basically two different thermal effects have to be considered for comparing the heat-up behavior of the standard and the contoured substrate. The center section heats-up faster for the standard substrate due to the higher gas velocity (cascade effect) [13], which allows the concentration of heat energy on a smaller cross section. For the outer area the contoured substrate heats-up faster, because there is more flow forced into this region. However the inlet temperature in the outer area is much lower compared to the center section, which generally delays the light-off in that region compared to the center. The overall performance will result from the interaction of both effects and will be very dependent on the radial temperature gradient in the gas phase. A potential improvement for the contoured substrate converter is the reduction of the temperature difference in the gas phase by minimizing the heat absorption of the pipe and cone materials. In this context the use of thin inner exhaust pipes and cones might be helpful for future evaluations [14]. The canning used in this experiment was been optimized concerning heat absorption during the light-off phase.

The steady state emissions performance of the converter systems has been evaluated using the stationary dynamometer set-up. The conversion efficiency was determined after the converter system was in thermal equilibrium using an average period of 200 seconds. The hydrocarbon remainder describing the difference between maximum (100%) and actual conversion efficiency is used for illustration purposes.

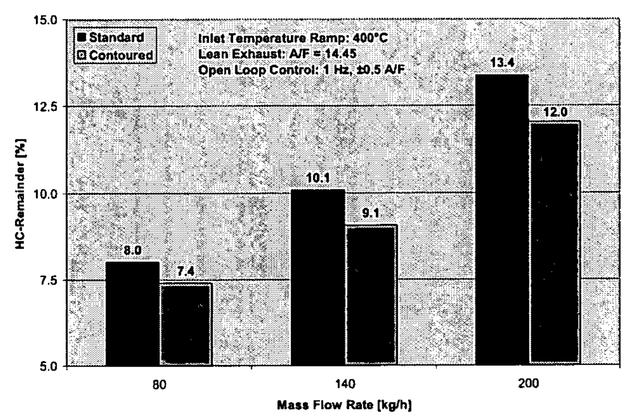

Figure 19. Steady-State HC emissions performance

Higher conversion efficiencies resulting in lower HC-remainder values were measured under each flow condition for the converter with the contoured substrate. As expected, the differences increase with higher mass flow rates with a maximum difference of 1.4% occurring at a flow rate of 200 kg/h. The reason for the improvement is seen in both the increased converter volume and the improved flow distribution. Further investigations are needed to quantify the impact of the individual effects.

As described above, more uniform and overall less severe aging is expected for the contoured substrate converter. In this experiment, a short aging duration of 50 hours was chosen. Larger effects should be seen with increased aging times.

CONCLUSIONS

- The utilization of the space in the inlet cone allows an increase of the substrate volume in the same space envelope. For the investigated converter system this results in a volume increase of about 15%.
- A major improvement in flow distribution can be achieved by using the proper design of the contoured substrate (up to 20%). The design can be optimized by Computational Fluid Dynamics (CFD). All three applied techniques, i.e. CFD, flow distribution measurements and flow visualization are in excellent qualitative agreement.
- The increased volume of the converter results in a higher pressure drop at higher flow rates for the contoured converter. Slightly lower or equivalent pressure drop is expected for equal volume converter systems.
- Initial durability investigations on a thermal cycling test did not result in any failure or degradation of the monolith and mounting system. At this juncture, the durability of the contoured converter system is not seen as a critical issue.
- The light-off performance was very similar between the converter systems. However, very different thermal behavior during the heat-up phase was found due to the differences in flow distribution. The temperature field over the cross-section of the converter with the contoured substrate is more uniform. Optimized canning might allow use of the contoured substrate to its fullest potential. Temperature gradients of the exhaust gas over the cross-section of the pipe and cone are the key issue.
- An improvement in steady-state emissions performance was determined with the contoured substrate due to the improved flow distribution and increased converter volume.
- Future work has to concentrate on the emissions performance of the converter system using the contoured substrate. A better understanding of the effects of improved flow distribution and increased volume has to be developed. Furthermore, the effects of more severe aging and thermally optimized canning on light-off performance should be subject of future investigations.

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NOMENCLATURE

$v_{space,l}$: local space velocity in 1/s
v_l: local velocity in m/s

$\overline{v}_{space,sub}$: average space velocity over the substrate cross section in 1/s

$\overline{v}_{pipe}$: average velocity over the inlet pipe cross section in m/s
ω_l: local non-uniformity index
ω: overall non-uniformity index
L_l: local length of the substrate channel
A_{sub}: cross sectional area of the substrate in cm^2
γ: overall uniformity index